

Modified cold-dark-matter models in light of 53W091, an old galaxy at high z .

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ABSTRACT

The epoch of galaxy formation provides an important additional test of cosmological theories. Cold-dark-matter (CDM) models with cosmological constant (Λ) are designed to account for the observed excess power in galaxy distribution, but at the same time suppress the power on small scales pushing galaxy formation to recent epochs. We point out that the recently discovered high redshift galaxy, 53W091, with accurate age measurements (Dunlop et al 1996) provides a particularly important test of these models. In the flat Λ -dominated Universe, the redshift of formation of 53W091 decreases with decreasing Ω . However, in the modified CDM models decreasing Ω suppresses the small scale power in the density field and this effect turns out to be dominant. We estimate the mass of the galaxy and show that it represents a very rare and unlikely event in the density field of such models. Similar problems would occur in other modifications of the CDM cosmogonies.

Subject headings: cosmology: theory — cosmology: dark matter — galaxies: formation — galaxies: individual (53W091)

High z objects constrain the small scale part of the spectrum of the primordial mass density field that cannot be probed directly by the large-scale structure or microwave background observations (Efstathiou & Rees 1988; Kashlinsky & Jones 1991; Kashlinsky 1993; Mo & Fukugita 1996). It was argued that the excess power observed in galaxy surveys (Maddox et al 1990, Picard 1991) can be explained within inflationary framework by invoking the low density flat Universe dominated by cosmological constant, $\Lambda \equiv 3H_0^2\lambda$, (Efstathiou et al 1990; hereafter LCDM) or by mixing CDM with massive neutrinos (Schaefer et al 1992; Klypin et al 1993; Taylor and Rowan-Robinson 1992; Davis et al 1992) and keeping $\Omega=1$ (hereafter MDM). However such models at the same time suppress power on small scales requiring late galaxy formation. The recently discovered high z galaxy, 53W091, (Dunlop et al 1996; hereafter D96) with red colors and old stellar population had to be formed at high z posing observational problem for such models. In the LCDM models, the redshift of its formation decreases with decreasing Ωh , but this also suppresses small scale power in the density field and delays galaxy formation. We show that the galaxy represents a very rare and unlikely event in the density field of the modified CDM models.

D96 have recently discovered an extremely red galaxy, 53W091, at $z=1.55$. Its red color is indicative of an old stellar population and its blue apparent magnitude $V=26$ implies a large luminous mass. They have been able to identify late-type stellar absorption features in the spectrum of the galaxy which allow one to determine the age. The spectrum for 53W091 was obtained in the range 2000 to 3500 Å, where the main contribution to the integrated light comes from the main sequence stars. The latter assumption is reasonable for galaxies with ages between 0.5 Gyr and 10 Gyr, when the blue giants have already become supernovae, yet the horizontal branch is still red ($B - V > 0.4$). (The galaxy is unlikely to be younger than 0.5 Gyr since in that case the spectrum would have been very blue contrary to what is observed.) The absence of the blue component also means that the galaxy can indeed be modeled with a single event of star formation. Hence D96 built a series of synthetic spectra at different ages with the main contribution coming from the main sequence stars. This was done using the set of stellar atmospheres models from Kurucz (1992) and a grid of stellar interior models from Jimenez & MacDonald (1997).

The best fit was found for the age of $t_{age}=3.5$ Gyr (D96). An independent evidence that the age of 53W091 cannot be less than 3 Gyr comes from transition breaks in the spectrum. The two of them, at 2600 and 2900 Å, were computed for different metallicities ($1/5 Z_\odot$, Z_\odot , and $2 Z_\odot$); the observed amplitudes showed that the breaks cannot be reproduced if $t_{age} < 3$ Gyr (D96). In order to check the robustness of the age determination, they computed synthetic spectra for models with different metallicities. For the case of $1/5 Z_\odot$ the best fit is obtained for $t_{age}=4.0$ Gyr. Only if the metallicity of 53W091 were as high as

$2Z_{\odot}$ the best fit is obtained for $t_{age}=3.0\text{Gyr}$, in good agreement with the determination from the breaks method. The numbers for t_{age} were computed in D96 assuming 53W091 to be an elliptical, i.e. assuming that the α -nuclei elements are enhanced with respect to the Sun with the typical enhancement factors being $[\alpha/\text{Fe}]=0.3\text{-}0.5$. Relaxing this assumption would change t_{age} by only 4% as detailed simulations of this effect have shown (Salaris, Chieffi & Straniero 1993). We therefore follow D96 and adopt for the present discussion the age uncertainty of the 53W091 galaxy to be no more than 0.5 Gyr with the most likely value of $t_{age}=3.5\text{Gyr}$. Pushing the age to the lower limit of the range, $t_{age}=3\text{Gyr}$, would at the same time require high metallicity ($Z \geq 2 Z_{\odot}$) typical of nuclei of ellipticals. (The galaxy was observed with an aperture of 4 " making the nucleus region unresolved).

In the context of inflationary cosmogonies, which generally require that the Universe be flat (Kashlinsky, Tkachev, Frieman 1994), these observations would force one to invoke a non-zero cosmological constant. Fig.1 shows the redshift z_{gal} at which the galaxy 53W091 must have formed its first stars for $\Omega+\lambda=1$ Universe. One can see that the value of z_{gal} decreases as both Ω and h decrease. On the other hand, in the LCDM cosmogonies the small-scale power is also reduced as the product Ωh decreases; this would at the same time delay collapse of first galaxies until progressively smaller z .

To quantify this we proceed in the manner outlined in Kashlinsky (1993). The power spectrum of CDM models is assumed to be initially of the Harrison-Zeldovich form. For tilted spectra (Cen et al 1992) our conclusions will be similar; this case is briefly discussed later in the *letter*. During radiation-dominated era only superhorizon fluctuations grow; this leads to the evolution/transfer in the original power spectrum. In the LCDM models, the shape of the power spectrum does not change after the matter-radiation equality and until fluctuations turn non-linear and collapse. In the MDM models the evolution of the power spectrum shape stops after neutrinos become non-relativistic. We consider first the LCDM models. The normalization scheme chosen below is independent of the redshift, z_i , chosen to normalize the density field, provided the latter was still linear. Thus we take the power spectrum at some early epoch, z_i , to be $P(k) \propto k T^2(k)$ with the transfer function whose shape is fixed by the horizon scale at the matter-radiation equality $\propto (\Omega h^2)^{-1}$. It is parametrized after Bardeen et al (1986): $T(k) = \ln(1 + a_0 k) [1 + a_1 k + (a_2 k)^2 + (a_3 k)^3 + (a_4 k)^4]^{-1/4} / a_0 k$ with $a_0=0.6 a_1=0.14 a_2=0.43 a_3=0.35 a_4=2.34 (\Omega h)^{-1} \text{Mpc}$. In the normalization we adopt lowering Ωh increases large-scale power but at the same time suppresses it on small scales.

In order to compute the initial density field we normalize its rms to Δ_8 , the amplitude that the fluctuations over comoving scale $r_8 \equiv 8h^{-1} \text{Mpc}$ had to have at z_i in order to reach unity fluctuation in galaxy

counts today. I.e. any fluctuation that had amplitude of Δ_8 at z_i will grow to the amplitude $\sigma_8 \equiv 1/b$ at $z=0$, where b is the bias factor fixed by matching to the COBE results. With this normalization the rms fluctuation at z_i , $\Delta(M)$, over the mass-scale M is given by: $\Delta^2(M) = \Delta_8^2 \int_0^\infty k^3 T^2(k) W(kr) dk / \int_0^\infty k^3 T^2(k) W(kr_8) dk$ where $r(M) = 1.25(M/10^{12} M_\odot)^{1/3} (\Omega/h)^{-1/3} h^{-1} \text{Mpc}$ is the comoving scale containing mass M . $W(x)$ is the window function chosen to filter the density field. For brevity, the results we present are for the top-hat case, but the numbers for Gaussian $W(x)$ would not differ substantially. Once parameters Ω, Λ are specified the value of Δ_8 can be computed analytically.

In the expanding Universe density fluctuations grow until they reach a critical overdensity at which time they turn-around and collapse to form compact objects. In open Universe with zero cosmological constant the growth freezes at $1 + z_{in} \simeq \Omega^{-1}$; if the Universe is flat and has non-zero cosmological constant this occurs at $1 + z_{in} \simeq \Omega^{-1/3}$. We denote with $\delta_{col}(z)$ the overdensity the fluctuation had to have at z_i in order to complete its collapse at redshift z as is required in order to form first stars and is also implied by the total radius of 53W091 of only $(8-15)h^{-1} \text{Kpc}$. As usual in the gravitational clustering picture we assume that any region that had mass overdensity at z_i greater than $\delta_{col}(z)$ will collapse by redshift z (Press & Schechter 1974). Its value in the above normalization scheme can be characterized via $Q(z) \equiv \delta_{col}(z)/\Delta_8$ plotted in Fig.1 of Kashlinsky (1993). For the case of $\Omega + \Lambda = 1$ it can be approximated $Q(z) \simeq 3\Omega^{0.225} b^{2/3} (1+z)$ at $z > \Omega^{-1/3} - 1$; this is valid for the values of z_{gal} plotted in Fig.1. The advantage of this normalization scheme is that the value of $Q(z)$ is independent of the initial epoch where the density field is fixed, provided the latter is still in linear regime. Thus a “typical” structure that has collapsed by redshift z must in these models have total mass M such that $\Delta(M)/\Delta_8 > Q(z)$. Conversely, if one knows the mass of the galaxy that collapsed to form stars at z one can use the Press-Schechter prescription to estimate the probability of that happening in a given model.

In order to compute the total luminous mass of the galaxy we used the integrated synthetic spectra from D96. The flux was then scaled assuming the Miller-Scalo IMF until it matched the observed fluxes in all, V,J,H,K, bands from D96. The effect of changing the slope of the IMF on the total luminous mass is generally small: $\sim 1\%$ when the IMF slope, α , changes from 2.5 to 3.5. We computed the total mass in stars in the galaxy for different cosmologies. Table 1 summarizes the results assuming a single burst of star formation: the first three rows correspond to the Einstein-de Sitter Universe, $\Omega=1$, with $h=0.6$ for the three values assumed for metallicity of the galaxy and for the three values of t_{age} . The following three rows correspond to the open Universe and $h = 0.6$; the last three rows show variations with H_0 for $\Omega=1$. Increasing the metallicity, Z , of 53W091 decreases M , but the change is very small for reasonable values of

Z . Because of the increasing distances, for flat $\Omega+\lambda=1$ models the mass is even higher. E.g. for the flat Λ -dominated Universe with $\Omega=0.2$ the total stellar mass for 53W091 is $1.8 \times 10^{12} M_{\odot}$. The trends with H_0 and Ω are very similar to the $\Lambda=0$ case; for brevity we do not present the numbers here. In order to account for different rates of star formation we adopted the star formation prescription described in Chambers & Charlot (1990) and computed a series of integrated synthetic spectra with different values for the typical star formation rate parameter τ . The change in the total star mass for the different star formation laws is small, particularly in the likely case of $\tau < 2$ Gyr. Larger τ lead to $Z \gg Z_{\odot}$ and also give larger M : e.g. if $\tau \geq 3$ Gyr, the mass estimates shown in Table 1 increase by 37%. The numbers vary little with model or cosmological parameters and show that 53W091 has $\geq 10^{12} M_{\odot}$ in stars alone inside the aperture of 4".

These values for the total luminous mass are consistent with an alternative way to compute the mass assuming 53W091 to be an elliptical galaxy. The aperture diameter of 4" corresponds to the physical radius at $z=1.55$ of $8.5h^{-1}$ Kpc if $\Omega=1$ and $14h^{-1}$ Kpc if $\Omega=0.1$ and the Universe is flat. These radii are typical of luminous sizes of giant ellipticals as are the colours and stellar populations of 53W091. If 53W091 is assumed to be an elliptical then the fundamental plane (Dressler et al 1987) relations lead to the total luminous mass of $10^{12} M_{\odot}$ (Peacock 1996) inside the aperture of 4", in agreement with our estimates.

We therefore conclude that 53W091 is a 3.5 Gyr old galaxy at $z=1.55$, and has luminous mass of $\geq 10^{12} M_{\odot}$. Its age is not likely to be below 3 Gyr and its colours and other properties are consistent with it being an elliptical. The total mass (including dark matter) is likely to be a factor 10 larger in which case our conclusions will be much stronger.

How likely is it that such a massive galaxy of at least $10^{12} M_{\odot}$ has collapsed to form stars within the total radius of $\simeq (8-15)h^{-1}$ Kpc at the redshift plotted in Fig.1 for the LCDM models? The quantity $\zeta \equiv Q(z_{gal})\Delta_s/\Delta(M)$ is the number of standard deviations the galaxy that collapsed at z_{gal} on mass-scale M would be in a given model. In models where the primordial density field is assumed Gaussian, this quantity uniquely determines the number density of objects of this (or greater) mass. ζ depends on the bias parameter, $\propto b^{2/3}$, which is determined by fitting to the COBE/DMR data (Smoot et al. 1992, Bennett et al 1996). In general such normalization requires $b \sim 2$ for the LCDM models normalized to large-scale structure observed in galaxy catalogs (Kashlinsky 1992, Efsthathiou, Bond & White 1992). The normalization procedure has been discussed in great detail for the LCDM models in Stompor, Gorski & Banday (1995) for the two-year COBE/DMR maps. The bias factor implied by the normalization of the LCDM models to the microwave background anisotropies is plotted there in Fig.3b vs Ωh^2 . For the range of Ωh^2 relevant to this

discussion this dependence of b on Ω_B is weak for the values of Ω_B consistent with the standard Big-Bang nucleosynthesis (SBBN). Increasing Ω_B above the SBBN values would lead to further suppression of the small-scale power, whereas decreasing it would not lead to any significant small-scale power increase. Note also, that normalising the spectrum to the four year COBE/DMR data (Bennett et al 1996) would increase b by $\simeq 10\text{-}15\%$. The values of ζ for $M=10^{12}M_\odot$ are plotted versus Ω in Fig.2 for $\Omega+\lambda=1$ for various values of t_{age} and h . As in Fig.1 solid lines correspond to $t_{age}=3\text{Gyr}$, dotted to 3.5 and dashes to 4 Gyr. Three types of each line correspond to $h=0.6, 0.8$ and 1 going from bottom to top at large values of Ω at the right end of the graph. The line for $t_{age}=4\text{Gyr}$ and $h=1$ lies above the box. As the figure shows, this galaxy must represent an extremely rare fluctuation in the density field specified by the LCDM models.

For Gaussian density field the probability of the region collapsing by the redshift z_{gal} would be $P_M = \frac{1}{2}\text{erfc}(\zeta/\sqrt{2})$. The Press-Schechter prescription works best in the limit of high peaks, $\zeta \gg 1$, and allows one to compute the number density of the collapsed objects of mass greater than M as $n(> M) = 2\rho \int_M^\infty \frac{\partial P_M}{\partial M} d\ln M$; “2” being the “fudge” factor traditionally introduced to normalize the counts of objects correctly in the Press-Schechter formalism (Peacock & Heavens 1990, Bond et al 1991). Fig.3a shows the expected comoving number density of such galaxies, $n(> M)$, in units of $(h^{-1}\text{Gpc})^{-3}$ vs the mass for $t_{age}=3.5\text{Gyr}$. As was discussed the luminous mass of 53W091 is $>10^{12}M_\odot$ and the total mass must be at least a factor of 10 larger. The numbers for the comoving number density $n(> M)$ in Fig.3 were computed for $\Omega=0.1, 0.2, 0.3$ and $h=1, 0.8, 0.6$. The models not shown lie below the box. Since $n(> M)$ is mainly determined by the corresponding ζ one can easily combine Fig.3a and Fig.2 to estimate the expected number densities at different t_{age} .

One can conclude from Fig.3a that within the framework of the LCDM models this object must be extremely rare in the Universe. There exists a narrow range of parameters (total mass of $10^{12}M_\odot$, age of $<3\text{ Gyr}$, $\Omega=0.1$ and $h\geq 0.8$) where one expects to find a few of such objects with each horizon, $R_{hor}\simeq 6h^{-1}\text{Gpc}$ for $\Omega=1$, but for most cases the number density of such objects is less than one per horizon volume. Comparison with Fig.1 shows that the models that allow the largest number of such galaxies are the ones that also place it at the lowest z_{gal} . If indeed more such galaxies with old stellar populations are found at high z , this would be difficult to explain within the LCDM models. It is interesting to note in this context the recent discoveries of several (proto)galaxy candidates at $z\simeq 4.5$ (Hu & McMahon 1996) and $z>6$ (Lanzetta, Yahil & Fernandez-Soto 1996). The first case corresponds to two $Ly\alpha$ -emitting objects sufficiently far from the nearest quasar that they are identified as (proto)galaxies forming their first generation of stars (the spectra are consistent with a galaxy whose integrated light is dominated by

massive stars). Lanzetta, Yahil & Fernandez-Soto (1996) report the discovery of 6 objects at $z \simeq 6$. These objects have ultraviolet luminosities and sizes similar to nearby starbursting galaxies, and therefore they are identified with the first generation of stars in the forming galaxy.

Thus it appears that galaxies were already not uncommon at $z > 5$. Fig.3b plots the expected number density of such galaxies at $z=5$ vs their total mass for the LCDM models. The lines that are not drawn would appear below the box. It is interesting to see that the models that predict the most abundance of objects like 53W091 at the same time predict very few, if any, galaxies at $z \simeq 5$ and vice versa.

One possibility to account for 53W091 within the framework of the LCDM models may be to suppose that the stars formed in smaller collapsed regions that later merged into the observed galaxy. However, the galaxy looks like a normal old relaxed giant elliptical. The physical diameter size corresponding to the aperture of 4" at $z=1.55$ is 29, 20 and 17 h^{-1} Kpc for $(\Omega, \lambda) = (0.1, 0.9), (0.1, 0)$ and $(1, 0)$ respectively; this is typical of diameters of giant ellipticals. It would be hard to see how mergers could have led to the substructure dissipating its energy to collapse to what appears a normal elliptical radius in such a short time. The galaxy has very red colors, indicating no star formation for the past $t_{age} > 3$ Gyr, so this would further have to occur without significant star formation expected from merger events (Bender, Ziegler & Bruzual 1996). Indeed, if the galaxy had undergone mergers 3.5 Gyr ago, the following star formation events would have created a significant blue component in its spectrum contrary to what is observed. Thus it is likely that for at least 3.5 Gyr 53W091 did not undergo any major merging events and its mass 3.5 Gyr ago had to be the same. Even invoking mergers would not help much. At the relevant masses and the LCDM power spectra $\zeta \propto M^{0.1-0.15}$, so in order to decrease ζ appreciably 53W091 must have undergone a very large number of mergers in a short time.

The galaxy 53W091, its mass and its age are even more problematic for the MDM models which require $\Omega = 1$ and also suppress small scale power (van Dalen & Shaefer 1992) leading to late galaxy formation (Kashlinsky 1993, Klypin et al 1993, Ma & Bertschinger 1994). In this case the value of z_{gal} is > 5 if $h > 0.4$ and $t_{age} = 3$ Gyr. If $t_{age} = 3.5$ Gyr and $h > 0.4$ the redshift $z_{gal} > 9$. One can see that even at the values as low as $h \simeq 0.4$ the redshift at which this galaxy must have collapsed to form stars is significantly larger than allowed by the MDM power spectra (Ma & Bertschinger 1994). A similar problem would also exist for the tilted CDM model suggested to explain the excess power seen in galaxy catalogs (Cen et al 1992). Assuming the primordial index of the power spectrum ($\propto k^n$) to be $n=0.7$, as suggested in the tilted CDM model and taking the conservative values of $10^{12}M_{\odot}$ for the total mass of 53W091 and $t_{age} > 3$ Gyr gives $\zeta > 6.6b^{2/3}$ if

$h=0.45$ is assumed. Such models would require $b \simeq 2$ (Cen et al 1992) making this galaxy a $\zeta > 10$ -sigma event. If $n=0.8$ the value of $\zeta > 6b^{2/3}$. For $h=0.45$ and the standard CDM ($n=1$) which requires $b \simeq 1$ by the COBE/DMR data, but fails to account for the excess power seen in galaxy catalogs (Maddox et al 1990), 53W091 would correspond to $\zeta > 5.4b^{2/3}$ standard deviations of the primordial density field if the total mass were $10^{12}M_{\odot}$.

The observational properties of 53W091 and the findings of galaxy candidates at $z > 5$ suggest that the Universe contains more collapsed galaxies at high z than the modified CDM models would predict. Such objects can be most readily accommodated by assuming both 1) low Ω Universe and 2) the small-scale power in the primordial power spectrum in excess of that given by simple inflationary models. E.g. the necessarily high redshift of galaxy formation can be produced in string models (Mahonen, Hara & Miyoshi 1995) or in the phenomenological primeval baryon isocurvature model (Peebles 1987).

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Figure captions:

Fig.1. The redshift, z_{gal} , when star formation in 53W091 was completed is plotted vs Ω for $\Omega + \lambda = 1$ Universe. Solid lines correspond to $t_{age}=3$, dotted to 3.5 and dashes to 4Gyr. Three lines of each type correspond to $h = 0.6, 0.8, 1$ from bottom up.

Fig.2. ζ , the number of standard deviations of the primordial density field 53W091 should be in the flat Λ -dominated CDM models is plotted vs Ω . ζ scales $\propto b^{-2/3}$ and is plotted for b normalized to the second year COBE/DMR maps. It is plotted for the total mass of 53W091 of $10^{12}M_{\odot}$. Same notation as in Fig.1. Three types of each line correspond to $h=0.6, 0.8$ and 1 going from bottom to top at large values of Ω at the right end of the graph. The line for $t_{age}=4$ Gyr and $h=1$ lies above the box.

Fig.3. (a) the predicted number density, $n(> M)$, of galaxies like 53W091 with the redshift of formation plotted in Fig.1 is plotted vs their total mass in units of $10^{10}M_{\odot}$. Solid lines correspond to $\Omega = 0.1$: they are for $h = 1, 0.8, 0.6$ from top to bottom respectively. Dotted lines correspond to $\Omega = 0.2$ and $h = 0.8, 0.6$ from bottom to top; the line for $h = 1$ lies below the box. Dashes correspond to $\Omega = 0.3$ and $h = 0.6$. The lines not drawn fall below the box. (b) Same as in (a) only plotted at $z = 5$. All lines go from top to bottom in the decreasing order of $h = 1, 0.8, 0.6$.

Age (Gyr)	$1/5 Z_{\odot}$	Z_{\odot}	$2 Z_{\odot}$
3.0	1.0×10^{12}	0.9×10^{12}	0.8×10^{12}
3.5	1.2×10^{12}	1.1×10^{12}	1.0×10^{12}
4.0	1.3×10^{12}	1.2×10^{12}	1.1×10^{12}
Age (Gyr)	$\Omega = 0.2$	$\Omega = 0.3$	$\Omega = 0.4$
3.0	1.4×10^{12}	1.3×10^{12}	1.1×10^{12}
3.5	1.8×10^{12}	1.5×10^{12}	1.3×10^{12}
4.0	1.9×10^{12}	1.7×10^{12}	1.4×10^{12}
Age (Gyr)	$H_0 = 60$	$H_0 = 80$	$H_0 = 100$
3.0	1.1×10^{12}	1.4×10^{12}	1.7×10^{12}
3.5	1.5×10^{12}	1.9×10^{12}	2.3×10^{12}
4.0	1.7×10^{12}	2.0×10^{12}	2.4×10^{12}

Table 1: Total star mass of 53W091 determined from stellar models scaled to the observed flux.

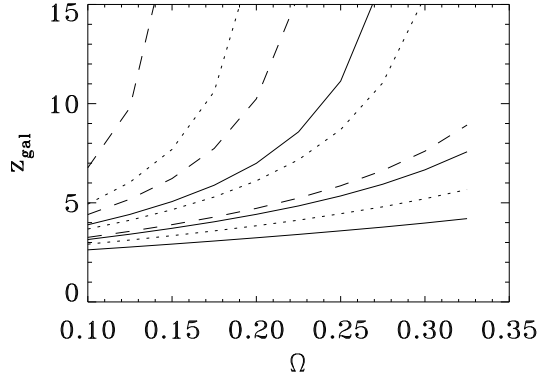


Fig. 1.—

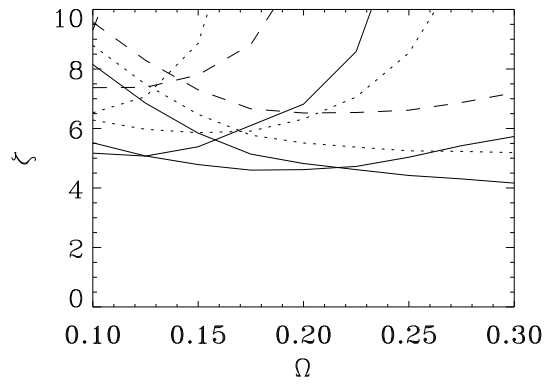


Fig. 2.—

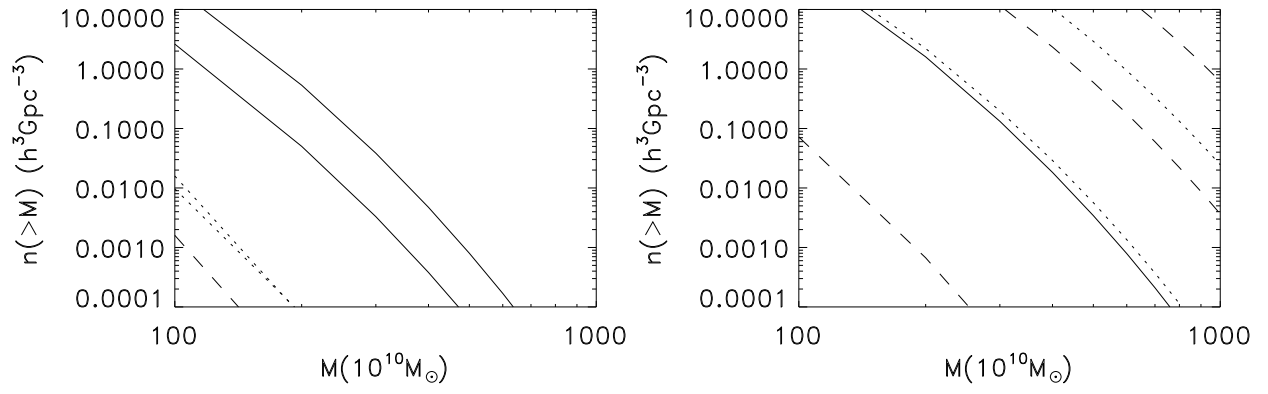


Fig. 3.—

